Creating a Terrain Model for Floodplain Mapping

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Abstract: A geographic information system (GIS) based approach is presented for the development of a terrain model based on stream channel representation of the U. S. Army Corps of Engineers Hydrologic Engineering Center’s River Analysis System (HEC-RAS) hydraulic model. As input, the approach requires a completed HEC-RAS simulation, a digital elevation model (DEM), and a GIS representation of the stream thalweg. The process begins with export of the channel data from HEC-RAS to GIS, followed by data conversion from hydraulic model coordinates to geographic coordinates. A digital terrain model is subsequently synthesized by merging HEC-RAS data for the stream channel with comparatively lower-resolution DEM data for the floodplain. The resulting surface model provides a good representation of the general landscape and contains additional detail within the stream channel. The accuracy of the terrain model is comparable to high-resolution terrain data acquired through aerial photogrammetry and can be used in conjunction with the new generation of river hydraulic models capable of accepting GIS terrain data. An example application to Waller Creek in Austin, Texas, is presented.

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Introduction

A fairly recent development in the field of stream hydraulic analysis has been the coupling of hydraulic modeling and geographic information systems (GIS). Currently, several commercial software packages are available that connect GIS and river hydraulic modeling. Through software such as HEC-GeoRAS (USACE 2000), cross-section parameters are extracted from a digital terrain model (DTM) and imported into a hydraulic model. After executing the hydraulic model, the output is processed for display and analysis in a GIS. However, most of the existing software solutions require a high-resolution DTM as the source of input cross-section descriptions. Unfortunately, DTMs with a sufficient resolution in stream channels for hydraulic modeling are not widely available and must be acquired through remote sensing and/or land survey.

In the absence of a high-resolution DTM as the source of cross-section descriptions used for the hydraulic modeling, current methods with which to map hydraulic model data in a GIS are inadequate. A method to create a DTM for hydraulic modeling from existing cross-section data may result in significant saving of both time and resources. The research described in this paper offers an approach for developing a DTM based on cross-section data stored in the U.S. Army Corps of Engineers Hydrologic Engineering Center River Analysis System (HEC-RAS) hydraulic model.

River hydraulic models such as HEC-RAS contain a wealth of detailed terrain data, typically developed from land surveys. But these high-resolution data are often stored in the coordinate system of the hydraulic model, a format that does not maintain the (X,Y) map coordinates of the cross sections. The primary difficulty with mapping hydraulic model data such as HEC-RAS stems from the fact that GIS and hydraulic models generally use entirely different coordinate systems to define their data. HEC-RAS is a 1D flow model in which the stream morphology is represented by a series of cross sections indexed by river station. The river station numbering increases from downstream to upstream. Each cross section is defined by a series of lateral and elevation coordinates (Fig. 1) that are typically obtained from land surveys. The cross-section coordinates are measured beginning at the left end of the cross section (looking downstream) and increasing until reaching the right end. In essence, HEC-RAS uses a relative coordinate system in which the coordinate of any given point is defined by its stream measure (river station) along a 1D thalweg line (Ms), cross section measure along a given cross section line (Mc), and elevation (Z) (Fig. 2). In contrast, GIS data are attributed with absolute map coordinates; the location of any given point in space is based on its easting (X), northing (Y), and elevation (Z). Where HEC-RAS represents the stream in relative model coordinates (Ms,Mc,Z), GIS represents the stream in absolute geographic coordinates (X,Y,Z).

In recent years, HEC-RAS has added the capability to import georeferenced cross-section data into its model coordinate system. However, for many HEC-RAS models developed in the past, the original geographic (X,Y) coordinates of the surveyed cross-section points are not known. In order to map these hydraulic

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model terrain data in a GIS, a methodology is required to convert the model coordinates into geographic coordinates.

Previous Work

Much of the work using GIS in conjunction with hydraulic modeling is relatively recent and not widely implemented. Digital elevation models (DEMs)—grids of regularly spaced elevation data—are commonly used in hydrologic analyses to represent flow paths of water over the land. However, the use of coarse DEM surfaces is generally not suitable for the high-resolution terrain representation required for hydraulic analysis of river channels. Because they cannot vary in spatial resolution, DEMs may define stream channels poorly in areas of complex relief (Carter 1988). For hydraulic modeling of river channels, the triangular irregular network (TIN) model is often better than a grid-based DEM. A TIN is a triangulated mesh constructed on the \((X,Y,Z)\) locations of a set of data points. The TIN model allows for a dense network of points where the land surface is complex and detailed, such as river channels, and for a lower point density in flat or gently sloping areas (Carter 1988). Recent studies have shown that, using computed water surface elevations and a DTM, accurate floodplain maps can be produced in a GIS (Buntz 1998).

Beavers (1994) performed some of the first connecting hydraulic modeling of river channels and GIS by developing a GIS-based tool named ARC/HEC2. ARC/HEC2 was used to pre- and postprocess terrain and floodplain data used for the HEC-2 hydraulic model. In 1997, Thomas Evans of HEC improved on the Beavers work with the release of a set of ArcInfo Macro Language scripts that serve as a pre- and postprocessor for HEC-RAS. In 1998, the Environmental Systems Research Institute (ESRI) released AVRAS, which uses ArcView as the pre- and postprocessing environment for hydraulic modeling in HEC-RAS. Today, several commercial computer software packages are available that connect GIS and river hydraulic modeling. The Danish Hydraulic Institute (MIKE 11 GIS) (DHI 2001), the Environmental Modeling Research Laboratory (Surfacewater Modeling System) (EMRL 2001), and the Hydrologic Engineering Center (HEC-GeoRAS) (USACE 2000) have developed software that couples hydraulic modeling with GIS.

Many of these software tools follow a similar theme for linking hydraulic modeling and GIS: cross-section parameters are extracted from a terrain model and imported into a hydraulic model. After the user executes the hydraulic model, the output is processed for display and analysis in a GIS. However, this technique requires a high-resolution DTM as the source of input cross-section descriptions. Unfortunately, DTMs with a resolution in stream channels sufficient for hydraulic modeling are not widely available and typically must be acquired through remote sensing. Moreover, these studies are unable to obtain accurate terrain data for areas perennially inundated by water and generally must be supplemented with bathymetric profiles obtained through land surveys. Hence, a method to integrate available DEMs with existing surveyed channel elevation data is important as it can result in saving of time and resources. The procedure described in this paper is an approach for developing a digital terrain model based on existing DEM and HEC-RAS channel data for cases in which a high-resolution DTM is not available.

Methodology

A methodology for building a digital terrain model from HEC-RAS cross-section data and a DEM is presented (Fig. 3). Waller Creek, a small urban stream located in Austin, Texas, is used as the study area to facilitate the presentation of the methodology. The procedure, which requires relatively few input data, has been automated in ArcView GIS through the development of several computer programs (Tate 1999). The data used for the Waller Creek study include the following:

- HEC-RAS input discharge and channel geometry files provided by City of Austin,
- 10 and 30 m resolution DEMs from Texas Natural Resource Information System (TNRIS),
- 1 m resolution digital orthophotography from TNRIS,
- Digital spatial data in vector format of Austin roads provided by City of Austin, and
- Spot elevation data of land surface terrain from Capital Area Planning Council (CAPCO).
Export HEC-RAS Geometry Data to Geographic Information System

In order to move into the GIS environment, the HEC-RAS cross-section data must be exported. After executing the HEC-RAS model, the results are written to an output report using the “generate report” option in the HEC-RAS file menu. The resulting report is a text file that contains input data describing cross-sectional geometry and stream flow rates, and output data describing computed water-surface profiles. (It should be noted that this text film is distinct from the one created using the “export GIS data” option, which is designed for use with an input digital terrain model.) The RAS output text file is read and key stream parameters are written to a table in ArcView. For each cross section, the extracted parameters include the river station number, the bank station locations, and the stream measure between adjacent cross sections (HEC-RAS reach lengths). In addition, the cross-section measure \((M_{cs})\) and elevation of all points (Fig. 1) are extracted. Using these points, the coordinates of the point possessing the minimum channel elevation are determined for each cross section as a proxy for the thalweg cross-section measure. It there are multiple points possessing the same minimum channel elevation, the cross-section measure of the thalweg is calculated by averaging the cross-section measure of all points possessing the same minimum elevation.

The distance along the cross section between each stream bank and the thalweg is calculated and stored in the cross-section parameter table. The remaining data stored in the cross-section parameter table are described in Table 1. The purpose of the data export step is to translate the HEC-RAS output from text file format into a tabular format recognizable in GIS. However, the cross-section coordinates are still tied to the HEC-RAS relative coordinate system. In order to map the floodplain terrain, the HEC-RAS cross sections must be georeferenced (assigned \(X, Y\) coordinates). This requires associating the HEC-RAS stream cross sections with a geographically referenced digital representation of the stream.

Stream Thalweg Definition

There are four primary ways to obtain a digital representation of the stream thalweg line:

1. Reach files—Reach files are a series of national hydrologic databases that uniquely identify and interconnect the stream segments or “reaches” that comprise the nation’s surface water drainage system. The recently released National Hydrography Dataset (NHD) is based on attributed 1:100,000 scale digital line graph hydrography (USGS 2001).

2. DTM-based delineation—Using the GIS raster analysis capabilities, a vector stream network can be derived using a DEM as the sole input. Alternatively, digital contour data can be used to help identify the thalweg.

3. Digital orthophotography—Using orthophotography as a base map, the stream thalweg can be digitized on-screen in a GIS. Dense vegetation along stream banks can be used to help identify the general stream location, but can also make it difficult to identify the exact thalweg location.

4. Land surveys—Data representing the stream thalweg may be available from land surveys. If these data are tied to a global coordinate system, they can be used as a vector representation of the stream.

Of the four methods listed above, the first three were evaluated for this study. Attempts to use reach files were discontinued early on because the stream thalweg representation was often inconsistent with the representation derived from a 30 m DEM and digitized.
Cross-Section Mapping

The first step in assigning map coordinates to the RAS cross sections is to compare the definition of the RAS stream to its GIS counterpart. It is possible, for example, that the GIS stream thalweg is defined to a point farther upstream (or downstream) than the RAS model, or vice versa. Hence, it is necessary to define the upstream and downstream boundaries of the RAS model onto the GIS digital stream. Intermediate stream definition points corresponding to known RAS cross-section locations, such as bridges or culverts can also be defined. Vector spatial data of City of Austin roads were used to help identify potential intermediate stream definition points. As the number of definition points increases, so does the accuracy of the resulting cross-section locations.

Once the stream definition points are established, the next step is to interpolate the cross sections between them. To do this, two attributes must be known for each cross section: location along the stream and orientation. Linear referencing is used to determine the location, or linear address, of each cross section along the GIS thalweg. Linear addresses come in two forms: relative and absolute. Relative addresses run from 0 to 100 and indicate the percent of total stream length at which a given address is located. In contrast, absolute addresses run from 0 to the length of the stream and represent distance along it in map units, such as kilometers or miles. Both address systems are used for this research. To begin with, a one-to-one relationship is established between selected records (known cross-section locations) in the cross-section parameter table and their associated stream definition points (Fig. 5). In this manner, absolute GIS addresses are assigned to the selected cross sections.

The HEC-RAS model thalweg definition is based on land surveys and topographic maps, whereas the basis for the GIS thalweg is aerial photogrammetry and digitizing. Because of differences in source data, the absolute addresses of the stream definition points are slightly different for the two thalweg lines. To account for the difference, relative addressing is used. For each segment of the thalweg located between adjacent definition points, the ratio of the stream measure of the HEC-RAS thalweg segment to that of the GIS thalweg segment is calculated. To determine the GIS thalweg segment length \( S_L \), the relative address of each definition point \( DP_1, DP_2 \) is calculated as a percentage along the total RAS stream length. The percentage difference is then multiplied by the total GIS thalweg length \( L \):

\[
S_L = \left[ \frac{DP_1 - DP_2}{100} \right] \cdot L
\]

The ratio of GIS and RAS segment lengths should be nearly one if the RAS stream measure and GIS thalweg line are accurate and the stream definition points are precisely placed. If the length of the RAS thalweg segment exceeds that of the GIS thalweg segment, the stream measures (HEC-RAS reach lengths) between adjacent cross sections are compressed by the ratio \( S_L \). If on the other hand, the RAS segment length is less than the GIS segment length, the stream measures between adjacent cross sections is expanded by the ratio \( S_L \). In this manner, an absolute linear address is assigned to each cross section, and the proportionality of RAS stream measure between cross sections is preserved. In the Waller Creek dataset, the value of \( S_L \) generally ranged between 0.98 and 1.02.

At this point, the cross-section addresses along the GIS thalweg are known, but not their orientation. The HEC-RAS model requires cross sections to be defined such that they are perpendicular to flow lines in the main channel and overbanks. Within relatively straight portions of the channel this typically means straight-line cross sections. Near bends in the stream, the cross sections are sometimes doglegged in the overbank to ensure per-
perpendicularly to flow. Although information concerning the orientation of each cross section is indicated on survey maps, it is not stored by HEC-RAS. Therefore, an assumption of orientation is required in order to map the cross sections in GIS. For this research, all cross sections are assumed to occur in straight lines perpendicular to the thalweg. In order to determine the bearing of a line perpendicular to the thalweg, the bearing of the thalweg itself ($\theta_t$) must first be known. The thalweg bearing is determined by calculating the bearing between two points located at a specified distance upstream, $(X_u, Y_u)$ and downstream $(X_d, Y_d)$ of the cross-section location along the stream:

$$\theta_t = \frac{(Y_u - Y_d)}{(X_u - X_d)}$$  \hspace{1cm} (2)

The bearing of the cross section ($\theta_{cs}$) is subsequently calculated as the negative inverse of the thalweg bearing (Fig. 6):

$$\theta_{cs} = -\left(\frac{1}{\theta_t}\right)$$  \hspace{1cm} (3)

The specified distance between the cross section and the points on the stream used for determining thalweg bearing [(X_u, Y_u) and (X_d, Y_d)] is termed here the “influence length” and is measured as a percentage of the total thalweg length (%L). The use of a small influence length produces cross sections that are locally perpendicular to the stream thalweg. However, this can result in intersecting cross sections near bends in the stream, a condition that is likely not representative of the surveyed cross sections. In contrast, use of a large influence length causes cross sections to be mapped perpendicular to the general bearing of the thalweg, a condition that may not accurately represent local flow patterns.

With the cross-section locations and orientations known, lines representing each cross section (and the individual points that make up each line) are mapped. If the resulting cross sections intersect near bends in the stream, they can be collectively remapped using a higher influence length. In addition, individual cross-section lines can be remapped if they have a known bearing (Anderson 2000). As the influence length increases, so does the departure from true perpendicular cross sections. For the Waller Creek data, an influence length of 5% is used to map the cross sections that corresponds to a distance of approximately 200 m. The influence length of 5% is the smallest value that avoids producing intersecting cross sections in the stream.

One important finding regarding the accuracy of the terrain model that results from this procedure regards cross-section spacing. For accurate hydraulic modeling, it is important to survey a greater number of cross sections where there are changes in cross-sectional geometry. In contrast, accurate terrain modeling demands a greater frequency of cross sections near bends in the stream. This is because the stream channel of the terrain model will only be defined at locations where cross sections intersect the thalweg. Insufficient cross-section spacing near bends in the stream will result in a terrain model with an inaccurate thalweg location between cross sections. To avoid this potential problem, the cross-section interpolation routine in HEC-RAS is employed. The routine is based on a string model consisting of chords that connect the coordinates of two adjacent cross sections ([USACE 2001]. Elevations are interpolated linearly along the chords. By specifying a minimum cross-section spacing, additional cross sections are added to the RAS geometry model. The end result is a terrain model possessing a more accurate thalweg representation. Fig. 7 illustrates this point, using a minimum spacing of 33 m for cross-section interpolation in HEC-RAS. Using a smaller spacing generates a thalweg that mimics the digitized thalweg to an even greater degree.

**Terrain Model Formation**

As a result of the cross-section mapping, all cross-section points ($M_{cs}, Z$) are assigned $(X, Y)$ geographic coordinates. Using these $(X, Y, Z)$ coordinates, a TIN model of the stream channel and floodplain can be constructed. However, a terrain model created solely from these vector data would be limited in extent by the cross-section endpoint while excluding the surrounding landscape. The DEM is the standard raster data model used for small-
scale representation of the general land surface. In order to create a TIN including both the channel and the general landscape, a method to integrate relatively low-resolution DEM data with comparatively higher-resolution vector floodplain data is required. It is important for the TIN to include areas both inside and outside the extent of the RAS channel cross-section data. Ultimately, the TIN will be used as ground elevation data for hydraulic modeling. A terrain model with a large aerial extent will add flexibility to the modeler during the selection of the location, orientation, and width of stream cross sections. By combining the channel and DEM data to form a TIN, the intended result is a seamless 3D landscape surface that contains detailed information within stream channels. This approach is employed to form a TIN model of the terrain and consists of the following steps (Fig. 8):

1. Clip the 30 m DEM to a manageable size to reduce processing time. For the Waller Creek study area, the original DEM has the same areal extent as a USGS 7.5 m quadrangle map, an area of approximately 170 sq km (~190,000 grid cells). In contrast, the clipped DEM covers only 9.5 sq km (~11,000 grid cells).

2. Perform a raster-to-vector conversion on the clipped DEM to create a point file of terrain elevations. In the conversion process, the centroids of DEM cells are converted to points, each attributed with the elevation of the cell.

3. Construct a single cross-section bounding polygon linking the cross-section endpoints.

4. Intersect the DEM points with the bounding polygon, and eliminate any DEM points that fall within the bounding polygon.

5. Extract the thalweg and bank points at each cross section and create 3D lines representing the stream thalweg and bank lines.

6. Build a TIN using the following input data sources: DEM points, cross-section lines, and 3D thalweg and bank lines. TIN nodes are formed from the DEM points and the vertices of the cross-section lines. The stream thalweg and bank station lines are enforced in the TIN as breaklines. Breaklines represent significant terrain features, such as a stream, ridge, or roadbed, which are indicative of a change in slope; TIN triangles do not cross breaklines.

Using this approach, a TIN model of the terrain is constructed such that the stream channel data supersed the DEM within the area for which they are defined and the DEM elevations prevail elsewhere (Fig. 9). The initial concern with this procedure was that there would be systematic differences between the channel and DEM data such that merging them into a TIN would result in a jump or drop in elevation at the cross-section endpoints. This indeed was the case: in many locations, the TIN has a ragged surface in the zone of transition between that RAS and DEM data that is not representative of actual terrain conditions. Given that two data sets have different collection times, methods, and resolution, it is not surprising that they are somewhat incompatible. Hence, the next task is to develop an approach with which to smooth the RAS-DEM data transition zone.

Terrain Model Integration with Digital Elevation Model

The cross-section point elevations for the Waller Creek HEC-RAS model were collected through various land surveys. In addition, City of Austin staff often estimated elevations at points distance from the main channel using available topographic maps. Hence, the accuracy of the HEC-RAS stream geometry data is greater within the channel than in the overbank areas. So in comparison to the HEC-RAS data, the DEM elevations outside the channel were considered to be the more accurate, albeit lower-resolution, data source. Also, the DEM represents the entire ground surface of the floodplain, not only the places where the cross sections exist. In order to smooth the transition zone, elevations in the cross sections and/or DEM data points should be altered. Because the cross-section elevation data in the floodway are considered less accurate, an interpolation approach is applied to these data. Within each cross section, the elevations of all points between the banks (within the channel) are left unchanged. At the end of each cross section, the elevation is assumed equal to
that of the DEM. A smoothing approach is applied to all surveyed cross-section points between the banks and cross-section endpoints. The approach is as follows for each cross section:

1. Measure the distance along the cross section between the bank and the cross-section endpoint on each side of the channel.
2. Identify the first cross-section point outside the bank and note its elevation.
3. Query the DEM elevation at that location.
4. Determine the cross-section measure of the point \((M_{cs})\), as a percentage of the total distance calculated in step 1. The new elevation of the point \((Z_n)\) is calculated as a weighted average of the original cross-section elevation \((Z_o)\) and the DEM elevation \((Z_{DEM})\):

\[
Z_n = Z_o \cdot (1 - M_{cs}) + Z_{DEM} \cdot M_{cs}
\]

For example, if the point is located 40% away from the bank station, the new elevation is the sum of 60% of the original cross-section elevation and 40% of the DEM elevation.

5. Repeat steps 1 through 4 for all cross-section points located outside the channel banks.

By employing the smoothing approach to the transition zone, the point elevations outside the channel banks will gradually trend toward the DEM elevation, moving from the bank station to the cross-section endpoint (Fig. 10). The original and smoothed cross sections are identical within the channel. Outside the channel, the elevation of the smoothed cross section falls somewhere between the original and DEM elevation. There may be instances in which areas outside the channel contain features that should not be smoothed, such as a floodwall, roadbed, or berm. This type of problem could be avoided on an individual cross-section basis by defining the beginning of the transition zone using a user-specified control point in lieu of the channel bank. Alternatively, the original unsmoothed cross section could be used to replace the smoothed cross section. Following the correction of specific cross sections, the terrain TIN is reconstructed using the smoothed cross-section theme as input. In the smoothed TIN, the zone of transition cannot be discerned.

**Results**

In order to assess the accuracy of the terrain model, it is compared with existing DTMs. Fig. 11 shows a comparison of the smoothed
cross section with profiles from 10 and 30 m DEMs. The figure illustrates why DEM surfaces are generally not suitable for the large-scale terrain representation required for hydraulic analysis of river channels. In general, the DEMs provide a sufficiently accurately representation of the floodplain, but the terrain description within the channel is inaccurate because the data are too coarse. As a better comparison of the accuracy of the terrain TIN, it is compared with a high-resolution DTM developed from Capitol Area Planning Council (CAPCO) spot elevation data. The CAPCO data were collected by aerial photogrammetry between 1996 and 1998 and have a high resolution with a data point density of up to one per square foot in some areas. Fig. 12 shows cross-section profiles based on the terrain TIN and CAPCO DTMs. This profile is only one of many, but serves to illustrate the primary differences between the DTMs observed at many other cross sections. In general, the profile shapes are quite similar, but there are some general differences observed between the datasets:

- The thalweg elevations tend to be shallower in the CAPCO DTM. The effect is more pronounced for profiles with deeper main channels and is likely due to limitations in aerial photogrammetry; it is very difficult to acquire accurate elevation data for areas inundated by water through photogrammetric methods. The surveyed cross sections that form a basis for the terrain TIN include field measurements and thus are judged to provide a better representation of the stream channel.
- A horizontal offset in the thalweg location is observed in some cross sections. Given that the profile shapes are similar, the offset is likely indicative of differences between the CAPCO stream thalweg and the digitized thalweg representation used in this research. The digitized thalweg representation could be improved by use of higher resolution orthoimagery or through delineation based on a DTM.
- The terrain TIN provides a superior topographic representation near the channel banks. The stream banks in the CAPCO DTM have characteristically gentle slopes. In contrast, the terrain TIN, based in part on land survey data, contain steeper slopes along the stream banks.

Both the terrain TIN and CAPCO DTM have a high density of points within the channel. Hence, both terrain models could be used as a source of cross-sectional data for river hydraulic modeling using GIS-based hydraulic modeling tools such as HEC-GeoRAS, MIKE 11, or SIMS. The availability and cost of the input data are what distinguish the CAPCO DTM from the terrain model developed through this research. Although increasingly more cities and agencies are contracting aerial photogrammetry projects, high-resolution elevation data for stream channels are not widely available. In contrast, 30 m DEMs and HEC-RAS models that are the primary inputs for the terrain DTM are available for many areas. Of course, the quality of the terrain TIN will depend upon the quality of the input HEC-RAS and DEM data. It is, however, significant that data of comparable quality of standard aerial photogrammetric products can be developed using existing data.

Conclusions

An approach for automated terrain modeling is presented. The work provides a method to synthesize a terrain model from HEC-RAS cross-section data and a coarse digital elevation model (DEM). As inputs, the approach requires a completed HEC-RAS model simulation, a DEM of the study area, and a GIS representation of the stream thalweg line. The output is a TIN model of the terrain that describes the terrain of the stream floodplain and contains additional detail with the stream channel.

The main limitation of this approach is the assumption of straight-line cross sections in the (X,Y) plane. Although information concerning the orientation of each cross section is indicated on survey maps, it is not routinely stored in HEC-RAS models. In order to map the cross sections, the approach in this study assumes that all cross sections occur in straight lines. The effect of the straight-line assumption on the accuracy of the resulting terrain models varies with the distance from the stream channel. Within the channel and near the stream banks, the effects of the straight-line assumption are minor because surveyed cross sections are not likely to be doglegged. Moreover, the distance from the stream thalweg is small in these areas, so changes in cross-section orientation have little effect on the accuracy of the terrain model. As the distance along the cross section away from the channel increases, so does the likelihood of incorrectly mapping the cross section. This is especially true of cross sections near bends in the stream, where the survey work maps may indicate a dogleg. It is therefore critical to represent the orientation of the cross sections accurately within the GIS, using the methods described herein.

Despite the limitations of the straight-line assumption, the research provides an important methodology for terrain modeling. As local and state governments increasingly invest in photogrammetric studies, more detailed DTMs will become available. However, these studies are unable to obtain accurate terrain data for areas perennially inundated by water and typically must be supplemented with bathymetric profiles through land survey. Hence, the method to integrate the DEMs with existing surveyed channel elevation data is important as it can result in saving time and resources. The resulting terrain DTM accurately describes both the general floodplain and channel morphology at a large scale required for hydraulic modeling. Currently, there are no adequate methods with which to integrate hydraulic model terrain data with a DEM. The terrain model produced by the approach is detailed in the stream channel, but also represents the general landscape and is comparable in quality to terrain model data acquired solely through aerial photogrammetry.
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Notation

The following symbols are used in this paper:

- DP = stream definition point;
- \( L \) = length of GIS thalweg;
- \( M_{cs} \) = cross-section measure;
- \( S_L \) = segment length of GIS thalweg;
- \( X \) = easting;
- \( X_d \) = easting of downstream point;
- \( X_u \) = easting of upstream point;
- \( Y \) = northing;
- \( Y_d \) = northing of downstream point;
- \( Y_u \) = northing of upstream point;
- \( Z \) = elevation;
- \( Z_{DEM} \) = DEM elevation;
- \( Z_n \) = cross-section point elevation after smoothing;
- \( Z_o \) = original cross-section point elevation;
- \( \theta_{cs} \) = cross-section bearing; and
- \( \theta_t \) = thalweg bearing.

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